

Spin-isospin Response in Finite Nuclei from an Extended Skyrme Interaction

Peiwei Wen^{1,2}, Li-Gang Cao^{1,3,4,5}, J. Margueron⁶, H. Sagawa^{7,8}

¹*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*

²*University of Chinese Academy of Sciences, Beijing 000049, China*

³*State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China*

⁴*Kavli Institute for Theoretical Physics China, CAS, Beijing 100190, China*

⁵*Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator of Lanzhou, Lanzhou 730000, P.R. China*

⁶*Université de Lyon, Université Lyon 1 and CNRS/IN2P3, Institut de Physique Nucléaire de Lyon, 4 rue Enrico Fermi, 69622 Villeurbanne, France*

⁷*Center for Mathematics and Physics, University of Aizu, Aizu-Wakamatsu, Fukushima 965-8580, Japan and*

⁸*RIKEN, Nishina Center, Wako, 351-0198, Japan*

The magnetic dipole (M1) and the Gamow-Teller (GT) excitations of finite nuclei have been studied in a fully self-consistent Hartree-Fock (HF) plus random phase approximation (RPA) approach by using a Skyrme energy density functional with spin and spin-isospin densities. To this end, we adopt the extended SLy5st interaction which includes spin-density dependent terms and stabilize nuclear matter with respect to spin instabilities. The effect of the spin-density dependent terms is examined in both the mean field and the spin-flip excited state calculations. The numerical results show that those terms give appreciable repulsive contributions to the M1 and GT response functions of finite nuclei.

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I. INTRODUCTION

The properties of spin asymmetric matter are still very difficult to access experimentally since the ground states of nuclei have a weak or an almost zero spin-polarization: even-even spherical nuclei are not spin-polarized, while their closest odd nuclei can be weakly spin-polarized by the last unpaired nucleon, but with a moderate impact on the ground-state energy [1]. In well deformed nuclei, ground-state spin and parity assignments are still difficult to predict globally [2]. It is therefore difficult to probe the nuclear interaction in spin and spin-isospin channels from the ground-state properties of nuclei. However, in the excitation spectra of nuclei, some collective modes can provide a unique opportunity to explore the nuclear interactions in spin and spin-isospin channels [3–5]. The M1 and GT excitations are the most common collective modes of spin and spin-isospin types in nuclei. These modes have been extensively studied during the last decade and much information on spin and spin-isospin excitations becomes now available [5, 6]. They are of interest not only in nuclear physics but also in astrophysics. They play, for instance, an important role in predicting β decay half-lives of neutron rich nuclei involved in the r-process of the nucleosynthesis [7]. In core-collapse supernova, the GT transitions of pf-shell nuclei give an important contribution to the weak interaction decay rates that play an essential role in the core-collapse dynamics of massive stars [8–10]. The neutrino-induced nucleosynthesis may take place via GT processes in neutron-rich environment [11]. For neutrino physics and double β decay, accurate GT matrix elements are necessary to understand the nature of neutrinos [12].

In the beginning of the 1980s, GT experiments made great progress when the (p,n) facility at the Indiana University Cyclotron Facility became operational. In

1981, the Skyrme SGII interaction was designed to give, for the first time, a detailed description of the GT data [13]. Some other Skyrme interactions, such as SLy230a & SLy230b [14], SLy4 & 5 [15], SkO [16], and more recently SAMi [17], have been determined with a special care of the spin and spin-isospin properties of nuclear matter and nuclei. Calculations of GT within the relativistic framework were done more recently [18, 19]. The relation between the spin or the spin-isospin excitations and the central part of the nuclear interaction is however not a one-to-one relation and other effects should be considered such as the spin-orbit splitting of the single-particle states and the residual spin-orbit interaction in the RPA calculations [20].

Recently an extension of the Skyrme interaction, including spin-density and spin-isospin density dependent terms, was proposed by some of the present authors [1, 21]. At variance with predictions in nuclear matter of *ab initio* methods based on realistic bare interactions [22–25], most of the standard Skyrme interactions predict spin or spin-isospin instabilities beyond the saturation density of nuclear matter [26]. The additional parameters of the extended Skyrme interaction were therefore adjusted to reproduce the results given by microscopic G-matrix calculations better. The extension of the Skyrme interaction was designed to keep the simplicity of the standard Skyrme interaction and to remove the ferromagnetic instability or to shift it to larger density.

The extended spin-density dependent terms can improve the properties of the Skyrme energy density functional in spin and spin-isospin channels by adding the weak repulsive effect. For example, the dimensionless Landau parameter G'_0 is increased by about 0.3 for three interactions SLy5 [15], LNS [27] and BSk16[28]. In Refs. [1, 21], the authors explored the effect of spin-density dependent terms on the response functions and

the mean free path of neutrinos in nuclear matter as well as the ground state properties of finite odd nuclei. The model proposed in Ref. [1, 21] was constrained by microscopic G-matrix predictions in uniform matter. It will be quite interesting to investigate the effect of the proposed extension of the Skyrme interaction for the spin and spin-isospin excitations of finite nuclei. In the present work, we study the contribution of spin-density dependent terms to the M1 and GT excitations in finite nuclei ^{90}Zr and ^{208}Pb with a fully self-consistent HF plus RPA framework [29]. The SLy5 Skyrme parameter set is employed in our calculations by adding the spin-density dependent terms. The new parametrization is called as SLy5st, which is the same used in Refs. [1, 21]. In present study we switch on and off the spin-density dependent terms in ground states and excited states calculations to see how much they affect the spin and spin-isospin response functions in finite nuclei.

This paper is organized as follows. In Sec. II we will briefly report the theoretical framework of the RPA based on the Skyrme interaction and its extension. The results and discussion are presented in Sec. III. Section IV is devoted to the summary and perspective for future.

II. FORMULA

We adopt the standard form of Skyrme interaction with the notations of Ref. [15]. The two nucleons are interacting through a zero-range, velocity-dependent and density-dependent Skyrme interaction with space, spin and isospin variables \mathbf{r}_i , $\boldsymbol{\sigma}_i$ and $\boldsymbol{\tau}_i$ which reads [15]:

$$\begin{aligned} V(\mathbf{r}_1, \mathbf{r}_2) = & t_0(1 + x_0 P_\sigma) \delta(\mathbf{r}) \\ & + \frac{1}{2} t_1(1 + x_1 P_\sigma) [\mathbf{P}'^2 \delta(\mathbf{r}) + \delta(\mathbf{r}) \mathbf{P}^2] \\ & + t_2(1 + x_2 P_\sigma) \mathbf{P}' \cdot \delta(\mathbf{r}) \mathbf{P} \\ & + \frac{1}{6} t_3(1 + x_3 P_\sigma) \rho^\alpha(\mathbf{R}) \delta(\mathbf{r}) \\ & + i W_0(\sigma_1 + \sigma_2) \cdot [\mathbf{P}' \times \delta(\mathbf{r}) \mathbf{P}], \end{aligned} \quad (1)$$

where $\mathbf{r} = \mathbf{r}_1 - \mathbf{r}_2$, $\mathbf{R} = \frac{1}{2}(\mathbf{r}_1 + \mathbf{r}_2)$, $\mathbf{P} = \frac{1}{2i}(\nabla_1 - \nabla_2)$, \mathbf{P}' is the hermitian conjugate of \mathbf{P} (acting on the left), $P_\sigma = \frac{1}{2}(1 + \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)$ is the spin-exchange operator, and $\rho = \rho_n + \rho_p$ is the total nucleon density. Within the standard formalism, the total binding energy of a nucleus can be expressed as the integral of a Skyrme density functional [15], which includes the kinetic-energy term \mathcal{K} , a zero-range term \mathcal{H}_0 , the density-dependent term \mathcal{H}_3 , an effective-mass term \mathcal{H}_{eff} , a finite-range momentum dependent term \mathcal{H}_{fin} , a spin-orbit term \mathcal{H}_{so} , a spin-gradient term \mathcal{H}_{sg} , and a Coulomb term \mathcal{H}_{Coul} .

The Skyrme interaction has been extended to include spin-density dependent terms which can improve the properties of the energy density functional in the spin and spin-isospin channels [21]. That is

$$\begin{aligned} V^{\text{add.}}(\mathbf{r}_1, \mathbf{r}_2) = & \frac{1}{6} t_3^s(1 + x_3^s P_\sigma) [\rho_s(\mathbf{R})]^{\gamma_s} \delta(\mathbf{r}) \\ & + \frac{1}{6} t_3^{st}(1 + x_3^{st} P_\sigma) [\rho_{st}(\mathbf{R})]^{\gamma_{st}} \delta(\mathbf{r}), \end{aligned} \quad (2)$$

where $\rho_s = \rho_\uparrow - \rho_\downarrow$ is the spin density and $\rho_{st} = \rho_{n\uparrow} - \rho_{n\downarrow} - \rho_{p\uparrow} + \rho_{p\downarrow}$ is the spin-isospin density. The spin symmetry is satisfied if the power of the density dependent terms γ_s and γ_{st} are both even integers.

In the following study, the spin-density dependent terms (2) are added to the original Hamiltonian. Then the density dependent part of the Skyrme energy density functional,

$$\mathcal{H}_3 = \frac{t_3}{48} \rho^\alpha [3\rho^2 + (2x_3 - 1)\rho_s^2 - (2x_3 + 1)\rho_t^2 - \rho_{st}^2], \quad (3)$$

has the extra density dependent terms \mathcal{H}_3^s and \mathcal{H}_3^{st} which read,

$$\mathcal{H}_3^s = \frac{t_3^s}{48} \rho_s^{\gamma_s} [3\rho^2 + (2x_3^s - 1)\rho_s^2 - (2x_3^s + 1)\rho_t^2 - \rho_{st}^2], \quad (4)$$

$$\mathcal{H}_3^{st} = \frac{t_3^{st}}{48} \rho_{st}^{\gamma_{st}} [3\rho^2 + (2x_3^{st} - 1)\rho_s^2 - (2x_3^{st} + 1)\rho_t^2 - \rho_{st}^2], \quad (5)$$

where $\rho_t = \rho_n - \rho_p$. The mean field potential U_q , where $q = n, p$, gets additional terms

$$\begin{aligned} U_q^{\text{add.}} = & \frac{t_3^s}{12} \rho_s^{\gamma_s} [(2 + x_3^s)\rho - (1 + 2x_3^s)\rho_q] \\ & + \frac{t_3^{st}}{12} \rho_{st}^{\gamma_{st}} [(2 + x_3^{st})\rho - (1 + 2x_3^{st})\rho_q]. \end{aligned} \quad (6)$$

In symmetric nuclear matter the Landau parameters [30] are also modified by the following additional terms

$$\frac{F_0^{\text{add.}}}{N_0} = \frac{t_3^s}{8} \rho_s^{\gamma_s} + \frac{t_3^{st}}{8} \rho_{st}^{\gamma_{st}}, \quad (7)$$

$$\frac{F_0'^{\text{add.}}}{N_0} = -\frac{t_3^s}{24} (2x_3^s + 1) \rho_s^{\gamma_s} - \frac{t_3^{st}}{24} (2x_3^{st} + 1) \rho_{st}^{\gamma_{st}}, \quad (8)$$

$$\begin{aligned} \frac{G_0^{\text{add.}}}{N_0} = & \frac{t_3^s}{48} \gamma_s (\gamma_s - 1) [3\rho^2 - (2x_3^s + 1)\rho_t^2 \\ & - \rho_{st}^2] \rho_s^{\gamma_s - 2} + \frac{t_3^{st}}{12} (x_3^{st} - \frac{1}{2}) \rho_{st}^{\gamma_{st}} \\ & + \frac{t_3^s}{24} (x_3^s - \frac{1}{2}) (\gamma_s + 1) (\gamma_s + 2) \rho_s^{\gamma_s}, \end{aligned} \quad (9)$$

$$\begin{aligned} \frac{G_0'^{\text{add.}}}{N_0} = & \frac{t_3^{st}}{48} \gamma_{st} (\gamma_{st} - 1) [3\rho^2 + (2x_3^{st} - 1)\rho_s^2 \\ & - (2x_3^{st} + 1)\rho_t^2] \rho_{st}^{\gamma_{st} - 2} - \frac{t_3^s}{24} \rho_s^{\gamma_s} \\ & - \frac{t_3^{st}}{48} (\gamma_{st} + 2) (\gamma_{st} + 1) \rho_{st}^{\gamma_{st}}. \end{aligned} \quad (10)$$

It was mentioned in [1, 21] that the spin-density dependent terms may lead very important effects on the spin and the spin-isospin properties of finite nuclei and nuclear matter. That is, the dimensionless Landau parameter G_0' is increased by about 0.3 for three interactions SLy5, LNS and BSk16. The improved Skyrme energy density functional in spin and spin-isospin channels will give also substantial contributions to the spin and spin-isospin excitations in finite nuclei, such as M1 and GT excitations. In present work, we will study the effect of spin-density dependent terms on the spin-dependent M1 and GT excitations in finite nuclei ^{90}Zr and ^{208}Pb .

The calculations are done within the Skyrme HF plus RPA. The well known RPA method [31, 32] in matrix form is given by

$$\begin{pmatrix} A & B \\ B^* & A^* \end{pmatrix} \begin{pmatrix} X^\nu \\ Y^\nu \end{pmatrix} = E_\nu \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} X^\nu \\ Y^\nu \end{pmatrix}, \quad (11)$$

where E_ν is the energy of the ν -th RPA state and X^ν , Y^ν are the corresponding forward and backward amplitudes, respectively. The matrix elements A and B are expressed as

$$A_{mi,nj} = (\epsilon_m - \epsilon_n)\delta_{mn}\delta_{ij} + \langle mj|V_{res}|in\rangle, \quad (12)$$

$$B_{mi,nj} = \langle mn|V_{res}|ij\rangle. \quad (13)$$

The p-h matrix elements are obtained from the Skyrme energy density functional including all the terms in Eqs. (3)~(5). The explicit forms of the matrices A and B are given in Ref. [29] in the case of Skyrme force. In general, the expression of the residual interaction is derived from the second derivative of the energy density with respect to the density ρ_{st} with the spin and isospin indices,

$$V_{res} = \sum_{sts't'} \frac{\delta^2 H}{\delta \rho_{st} \delta \rho_{s't'}}, \quad (14)$$

where H is the HF energy density functional. According to Eq. (14), the antisymmetrized particle-hole interaction induced by the spin-density dependent terms (2) are expressed as,

$$\begin{aligned} V_{res}^{qq} &= v_0^{qq} \delta(\vec{r}_1 - \vec{r}_2) + v_\sigma^{qq} \delta(\vec{r}_1 - \vec{r}_2) \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2, \\ V_{res}^{qq'} &= v_0^{qq'} \delta(\vec{r}_1 - \vec{r}_2) + v_\sigma^{qq'} \delta(\vec{r}_1 - \vec{r}_2) \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2, \end{aligned} \quad (15)$$

where the functions v_0 and v_σ depend only on the radial

coordinate r and their detailed expressions are given by

$$\begin{aligned} v_0^{qq}(r) &= -\frac{t_3^s}{12}(x_3^s - 1)\rho_s^{\gamma_s} - \frac{t_3^{st}}{12}(x_3^{st} - 1)\rho_{st}^{\gamma_{st}} \\ v_0^{qq'}(r) &= \frac{t_3^s}{12}(x_3^s + 2)\rho_s^{\gamma_s} + \frac{t_3^{st}}{12}(x_3^{st} + 2)\rho_{st}^{\gamma_{st}} \\ v_\sigma^{qq}(r) &= \frac{t_3^s}{48} \left[\gamma_s(\gamma_s - 1)\rho_s^{\gamma_s-2} \left(3\rho^2 - (2x_3^s + 1)\rho_t^2 - \rho_{st}^2 \right) \right. \\ &\quad \left. + \rho_s^{\gamma_s} \left((\gamma_s + 1)(\gamma_s + 2)(2x_3^s - 1) - 2 \right) \right] \\ &\quad + \frac{t_3^{st}}{48} \left[\gamma_{st}(\gamma_{st} - 1)\rho_{st}^{\gamma_{st}-2} \left(3\rho^2 + (2x_3^{st} - 1)\rho_s^2 \right. \right. \\ &\quad \left. \left. - (2x_3^{st} + 1)\rho_t^2 \right) \right. \\ &\quad \left. + \rho_{st}^{\gamma_{st}} \left(-(\gamma_{st} + 1)(\gamma_{st} + 2) + 2(2x_3^{st} - 1) \right) \right], \\ v_\sigma^{qq'}(r) &= \frac{t_3^s}{48} \left[\gamma_s(\gamma_s - 1)\rho_s^{\gamma_s-2} \left(3\rho^2 - (2x_3^s + 1)\rho_t^2 - \rho_{st}^2 \right) \right. \\ &\quad \left. + \rho_s^{\gamma_s} \left((\gamma_s + 1)(\gamma_s + 2)(2x_3^s - 1) + 2 \right) \right] \\ &\quad + \frac{t_3^{st}}{48} \left[-\gamma_{st}(\gamma_{st} - 1)\rho_{st}^{\gamma_{st}-2} \left(3\rho^2 + (2x_3^{st} - 1)\rho_s^2 \right. \right. \\ &\quad \left. \left. - (2x_3^{st} + 1)\rho_t^2 \right) \right. \\ &\quad \left. + \rho_{st}^{\gamma_{st}} \left((\gamma_{st} + 1)(\gamma_{st} + 2) + 2(2x_3^{st} - 1) \right) \right] \quad (16) \end{aligned}$$

We will use the following operator for M1 excitation,

$$\hat{F}_{M1} = \sum_{i=1}^A \{g_i^s \vec{s}_i + g_i^l \vec{l}_i\}, \quad (17)$$

where the spin g -factors are $g^s = 5.586$ for protons and $g^s = -3.826$ for neutrons, respectively, and the orbital g -factors are $g^l = 1.0$ for protons and $g^l = 0.0$ for neutrons, respectively, in unit of the nuclear magneton $\mu_N = e\hbar/2mc$. We will also study the charge-exchange GT excitations. The GT external operator reads

$$\hat{F}_{GT\pm} = \sum_{i=1}^A \vec{\sigma}(i)t_\pm(i). \quad (18)$$

III. RESULTS AND DISCUSSIONS

In Table I we show the parameters used in this study and the Landau parameters G_0 and G'_0 calculated with the corresponding Skyrme interactions. To keep the spin symmetry, we set γ_s and γ_{st} equal to 2. The values for the other parameters t_3^s , t_3^{st} , x_3^s and x_3^{st} are fixed by an optimal fit of the BHF results in spin and spin-isospin channels in a higher density region than the normal density. The ground state properties of nuclei ^{90}Zr and ^{208}Pb are calculated in the coordinate space with a box approximation. The radius of the box is taken to be 20 fm in which the continuum is discretized in the large box. The 8 oscillator shell is included as the particle states to build the RPA model space. All calculations

TABLE I: Parameters of the spin-density dependent terms t_3^s (in $\text{MeV}\cdot\text{fm}^{3\gamma_s-2}$), t_3^{st} (in $\text{MeV}\cdot\text{fm}^{3\gamma_{st}-2}$), x_3^s and x_3^{st} for the interactions SLy5st. We also show the dimensionless Landau parameters G_0 and G'_0 deduced from the original SLy5 and SLy5st, respectively.

	t_3^s	t_3^{st}	x_3^s	x_3^{st}	γ_s	γ_{st}	G_0	G'_0
SLy5	-	-	-	-	-	-	1.12	-0.14
SLy5st	0.6×10^4	2×10^4	-3	0	2	2	1.19	0.15

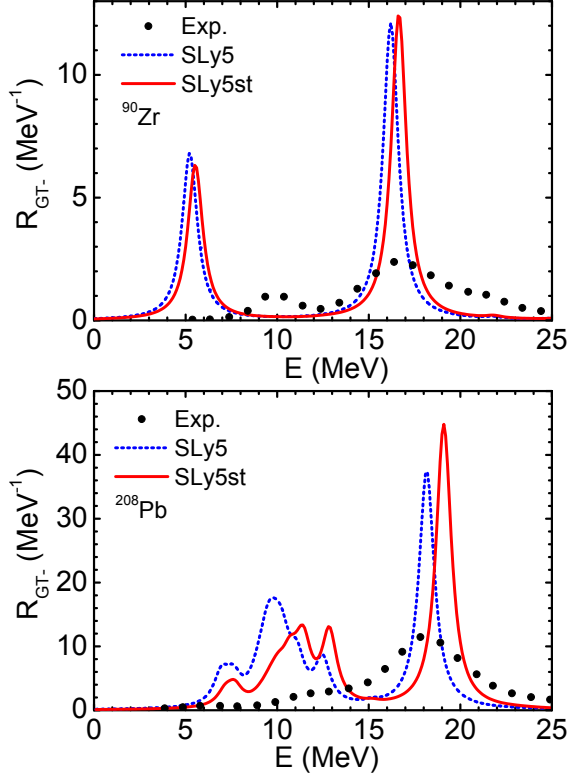


FIG. 1: (Color online) RPA Response functions of ^{90}Zr (upper panel) and ^{208}Pb (lower panel) for GT excitations calculated by the Skyrme HF plus RPA approach based on the SLy5 interaction. Solid (Dotted) line is the result given by including (excluding) the spin-density dependent terms. A Lorentzian smearing parameter equals 1 MeV. The experimental responses from Ref. [34, 35] are shown by the dots.

are performed within the SLy5 parameter set by including or excluding the spin-density dependent terms.

In Fig.1 we display the response functions for GT excitation in ^{90}Zr and ^{208}Pb calculated with and without the contribution of the spin-density dependent terms (2). The solid (dotted) line represents the results including (excluding) the spin-density dependent terms both at the HF and RPA calculations. The dots show the corresponding experimental GT response. As one can see from Fig.1, the inclusion of the spin-density dependent terms tends to slightly increase the high-lying strength on the one hand and to decrease the low-lying strength on the other hand. The excitation energies are shifted up in energy both the low-lying and high-lying strengths by the spin-dependent terms. Without the spin-density dependent terms, the centroid energies of the low-lying and high-lying strengths are 5.23 MeV (9.87 MeV) and 16.26 MeV (18.13 MeV) for ^{90}Zr

(^{208}Pb). Including the spin-density dependent terms, the centroid energies of the low-lying and high-lying strengths become 5.53 MeV (10.92 MeV) and 16.68 MeV (19.07 MeV) for ^{90}Zr (^{208}Pb). The energy shift is 0.3 MeV (1.05 MeV) for the low-lying and 0.42 MeV (0.94 MeV) for the high-lying states in ^{90}Zr (^{208}Pb). The energy shift given by the Skyrme HF plus RPA calculations is qualitatively the same as those estimated by the semi-classical Steinwedel-Jensen model for ^{208}Pb in Ref. [21]. The upward shift of the centroid energies can be understood as follows: the spin-density dependent terms give an strong repulsive contribution to the matrix elements of RPA for the GT calculations because the residual interactions or the Landau parameter G'_0 changes to be more positive from -0.14 to 0.15 when the spin-density dependent terms are included. It also can be seen that the RPA collective state located at 19.07 MeV with the spin-density dependent terms in ^{208}Pb is very close to the experimental GT excitation energy of 19.2 ± 0.2 MeV [33, 34]. For ^{90}Zr , the calculated values with or without the contribution of the spin-density dependent terms both are larger than the experimental value of 15.60 MeV [35].

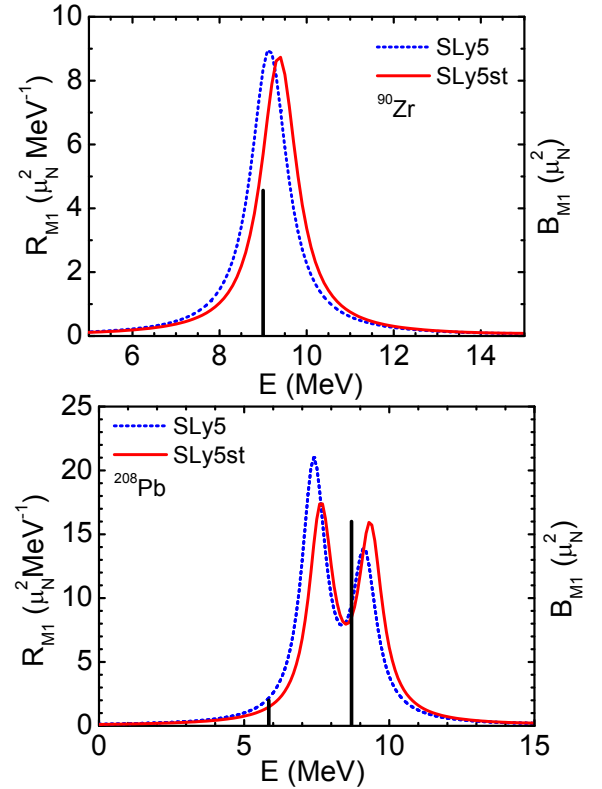


FIG. 2: (Color online) RPA Response functions of ^{90}Zr (upper panel) and ^{208}Pb (lower panel) for M1 excitations calculated by the Skyrme HF plus RPA approach based on the SLy5 interaction. Solid (Dotted) line is the result given by including (excluding) the spin-density dependent terms. A Lorentzian smearing parameter equals 1 MeV. The experimental $B(M1)$ values from Ref. [36–41] are shown by the bars.

We also investigate the effect of the extended Skyrme interaction on the M1 excitation by the RPA calculations for ^{90}Zr and ^{208}Pb . The results are shown in Fig. 2. The spin-density dependent terms are included or

excluded in the calculations to clarify their influence. For the RPA results of ^{208}Pb , the proton $1h_{11/2} \rightarrow 1h_{9/2}$ configuration contributes mainly to the lower energy peak of the response function, and the neutron $1i_{13/2} \rightarrow 1i_{11/2}$ configuration plays the main role in the higher energy peak. For ^{90}Zr , the M1 response function mainly comes from the neutron configuration of $1g_{9/2} \rightarrow 1g_{7/2}$. The results show that the inclusion of the spin-density dependent terms increases the energies of M1 states both in ^{90}Zr and ^{208}Pb . The peak energies of M1 excitation in ^{208}Pb are 7.6 MeV (7.4 MeV) for the lower one and 9.3 MeV (9.1 MeV) for the higher one with including (excluding) the spin-density dependent terms. The peak energy of the M1 excitation in ^{90}Zr are 9.4 MeV (9.1 MeV) by including (excluding) the spin-density dependent terms. The energy shift is less than 0.3 MeV for both ^{90}Zr and ^{208}Pb . The effect of the spin-dependent terms is predicted to be smaller on the distribution of the M1 response function compared with that on the GT excitation. This can be understood by the change of the Landau parameters when the spin-density dependent terms are included. The difference of G_0 which contributes to the M1 excitation is about 0.07 (from 1.12 to 1.19), while the change of G'_0 which plays the dominant role in GT excitation is about 0.3 (from -0.14 to 0.15). In Fig. 2 we show also the experimental data of the M1 excitations for ^{90}Zr and ^{208}Pb . The experimental data for the M1 excitations in ^{208}Pb are found at $E_x=5.85$ MeV for low-lying component and between $E_x=7.1$ and 8.7 MeV for the high-lying component [36–38], while in ^{90}Zr the M1 strengths exist between $E_x=9.0$ and 9.53 MeV [39–41]. We can see that the present theoretical results, taking or not taking into account the contribution of the spin-density dependent terms, slightly overestimate the experimental data in energy.

IV. SUMMARY AND PERSPECTIVE

In summary, we have studied the effect of the spin-density dependent terms of the Skyrme energy density functional on the M1 and GT giant excitations in ^{90}Zr and ^{208}Pb by the Skyrme HF plus RPA calculations.

The calculations are carried out with the SLy5 Skyrme interaction and the extended Skyrme interaction SLy5st, in which the spin-density dependent terms are added to the SLy5 parameter set to mimic the BHF results in spin and spin-isospin channels. Those terms are switched on and off in both the HF and the RPA calculations in this study. The inclusion of spin-density dependent terms is known to give no contribution to the ground state of even-even nuclei, while the residual interactions from the spin-density dependent terms give substantial repulsive effect and shifts the M1 and GT response function of finite nuclei to higher energy.

The main conclusion we can draw from the present study is that the spin and spin-isospin response functions can be changed without altering the ground-state properties. Since the parameters related to the spin-density dependent terms are introduced to the existing Skyrme interaction, it is marginal whether the new interaction improves the agreement with the experimental data of spin dependent excitations or not. The better strategy could be to perform a global fitting of the parameters of the spin-independent and spin-dependent density terms on the same foot. Recently, the effect of tensor force on the various response of nuclear systems has been studied extensively [42–44] and the important contributions to the spin and spin-isospin response in nuclear matter and finite nuclei are pointed out. It is a future challenge to include both the spin dependent terms and the tensor force in the parameter fit procedure. This study will be discussed in the forthcoming paper.

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